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APPLICATION OF JET IMPINGEMENT COOLING IN STEEL PRODUCTION: A REVIEW OF CONSTRAINS AND PROSPECTS

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ABSTRACT

Initial surface temperature, Leidenfrost Phenomenon effect on water jet impingement cooling and lack of heat transfer energy balance on steel cooling as the cause of high cost of steel, lack new steel properties emergence and incomplete data on jet impingement cooling respectively. These are the causes while designers are calling for reduction in cost of steel. Thus steel rolling mills are recommended to have combined nozzle headers for top surface and bottom surface cooling, while for research, Run-out table combine nozzle headers are to be designed, developed and installed. Also for a complete database on jet impingement cooling, top or bottom surface cooling in all existing literature needs to be done for completeness of the jet impingement database. Agricultural raw materials with paraffin oil is recommended for replacement or near substitute to water, expected to give a new steel grade property. Lower initial temperature of 500oC down to 400oC is recommended for lower steel cost of production.

KEYWORDS: Initial Surface Temperature, Leidenfrost Phenomenon, Steel Production & Jet Impingement Cooling

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Original Article

INTRODUCTION

Earlier and currently water has been the main jet impingement cooling liquid in steel industries. Research has gone into the analysis of water and its rate of cooling. Normally, impingement gap, flow rate, jet velocity speed of the plate and nozzle diameter have been the known parameters that affect the cooling rate and subsequently steel property. Several works have been done on the existing parameters using water as cooling liquid. However, recently few novel fluids with very little literature on impingement cooling are springing up, yet cannot address constrains associated with water and yet could not produce steel with new properties. Also, the process of cooling has constituted constrain and limitations to steel production. Earlier, top surface cooling has been the main process of steel cooling. Bottom surface has scarcely been reported, even when it is reported, it does not close the cycle of energy balance in the heat transfer process and either of the processes singly does not take care of the steel thickness. Initial surface temperature as well has constituted constrain for steel production in the area of cost effectiveness. Constrains of using single liquid-water as impingement liquid, having only a single surface cooling process and higher initial surface temperature has limited the production of steel without new steel properties and has not become cost effective in downstream steel market. The prospects to steel production with more properties are hinged on the expansion of the impingement liquids and cooling processes. Introduction of several new liquids from agricultural based materials and simultaneously or separately having top and bottom surface cooling to

balance the energy is needed.

Top Surface Cooling

Afzal et al, (2015) in their study of confined and unconfined multiple micro-jet impingement used top surface cooling and water for heat transfer. Onah, et al (2018) handled the top surface water cooling on a stationary plate with a transient heat transfer mode on variant nozzle diameters. Mozunmber et al, (2005)AndWoodfield et al, (2005) both conducted transient state heat transfer experiments on impingement cooling using water as the cooling fluid. Zhengdong, (2001)Studied the experiments and mathematical modelling of controlled run out Table cooling in a hot rolling mill- replica of industrial application using water top surface. Karwa, (2012)In his study of water jet impingement cooling of hot steel plates proposed temperature estimation for water cooling of hot steel plate. Karan et al, (2017) used the top surface cooling and water. Ahmed, (2016) Studied steady state water jet impingement cooling, using top surface. Maharshi, (2017) In his work modelled top surface water jet cooling using numerical analysis. Md Lokman et al, (2014)studied two sets of boundary conditions on top surface hot steel plate with water. In their work, the effect of Leidenfrostphenomenon affected their rate of cooling and the absence of bottom surface cooling affected the energy balance of the heat transfer process.

Bottom Surface Cooling

Monde et al, (1994) Using steady state heat transfer, carried out downward surface cooling with water as the cooling fluid. Mitsutakee et al, (2001)carried out an experiment on a transient boiling heat transfer with a single bottom water jet impingement cooling upward on a hot cylindrical copper block. Tang, (2012)Studied effect of sub cooling with single circular free surface jet on a downward facing hot surface. Noel, (2006)Studied boiling heat transfer on hot steel plate cooled by inclined circular bottom surface water jet. He focused on the inclined angle at the bottom of the hot steel plate. Using water Gilles et al, (2019) conducted a study on conventional bottom surface cooling, and their work centered more on the phase transformation of boiling regimes in cooling process of hot steel plate/strip. Again this process did not solve the problem of Leidenfrost rather gravitational effect was added to the already existing Leidenfrost phenomenon associated with water and the absence of top surface cooling affected the energy balance in the heat transfer process.

Conventional Jet Cooling

Jay et al, (2016), conducted a cooling experiments on the moving steel plate to correlate the independent parameters with dependent variables (cooling rate and CHF) by using a response surface methodology. The steel plate of grade AISI 304 was cooled from 900^{o}C to room temperature by using water jet nozzle. Alqash, (2015)in his study of a moving plate he tries to vary parameters in ROT involved in determining the cooling rate, they include: strip speed, strip temperature, and water jets configuration parameters which are: jet-to-jet distance and jet-to-plate gap, and water flow rate. Saeid et al, (2019) had mixed convection heat transfer co-efficient, details of jet impinging targeted moving heated plate, using Air jet impingement cooling with numerical analysis under steady laminar flow conditions.

The Leidenfrost phenomenon still affected water and the top surface could not balance the energy in the heat transfer process due to the absence of bottom surface cooling.

Inclined Jet Cooling

Qian et al, (2015), in the quest for a novel idea, introduced inclined jet impingement cooling, however, with fluid as water on top surface. Studying single jet in a bid to cool turbine vanes. Anuj et al, (2018) in their work numerically studied

inclined jet impingement cooling using air as the cooling fluid. Mohamed et al, (2012)experimentally investigated Hydrodynamic Flow Due to Obliquely Free Circular Water Jet Impinging on Horizontal Flat Plate. Kumar et al, (2018)in their numerical study of inclined air jet impingement cooling of cylinder carried out on an isothermal cylinder. A steady, incompressible, turbulence, three dimensional model was analyzed.

Leidenfrost phenomenon remains as long as the jet impingement fluid is water and the absence of the opposite angled jet cooling makes the heat transfer energy unbalanced.

Other Jet Impingement Fluids

Qi et al, (2018), used automatic transmission fluid as the impingement fluid on the top surface of a rotating device. Though Leidenfrost phenomenon is absent, heat transfer energy remains unbalanced due to lack of bottom surface on ATF jet impingement cooling.

Roy, (2011), carried out an experiment for quenching of stainless steel using single jet oil impingement cooling process on the bottom surface of the plate. Here the top surface is lacking though steel property may defer from that cooled with water, but the energy if not balance and the analysis will incomplete.

Avadhesh A et al, (2019), and Cemil et al, (2011), began by acknowledging the superiority of jet impingement cooling as always preferred over the other cooling methods due to its high heat removal capability. Their experiment was on rewetting behaviour of a hot horizontal downward facing hot surface by mist jet impingement, they may have succeeded in better flow controlled, but yet could not balance the energy in the heat transfer process.

Glynn et al, (2014), in their research investigated local heat transfer coefficients on single, axisymmetric, submerged and confined impinging air water jets simultaneously. Though, two fluids were used at the same time but only on top surface cooling.

Air Jet Cooling

Singh et al, (2019)and Ganatra et al, (2018)they focused their study mainly on the air slot jet impingement heat transfer with target surface on a steel plate. Mohan et al, (2017), in their work to investigate heat transfer on flat plate using jet impingement, considered air as their fluid heating on the top surface of the sampled specimen**.** Bobade et al, (2017), Modelled air flow distribution from axial fan over coils of hot rolled sheet by computational fluid dynamics- top surface cooling. Singh P et al, (2017), their main focus was to understand effect of conduction in finite thick solid wall heat transfer using air impingement cooling, concentrating on top surface cooling. Chougule et al, (2011)Analyzed multi-jet air impingement on hot plate using CFD. They observed that multi-jet impingement, spacing between the air jets play important role in top surface cooling.

Anand et al, (2017), this work reported preliminary-parametric analysis, intended for better understanding and comparison of micro impingement jets (0.25 mm) and macro jets (0.5 mm) for gas turbine vane cooling application. Muvvala et al, (2015), concentrated on surface roughness as hindrance from heat transfer using air. Just as the water jet impingement cooling, air jet behaves same, except that Leidenfrost phenomenon does not affect air yet heat transfer energy balance is absent.

Initial Surface Temperature

Literature has reported initial surface temperature of 600^{O}C to 900^{o}C in most publications, scarcely has it reported anything

lower. In industries, it is between 800ºC and 1000ºC. At the bottom surface, Zang (2004), Roy (2009) and Noel (2006) had 900ºC, 630ºC and 1200ºC respectively. Top surface has Onah et al (2018), Maharshi (2017), Jay et al, (2016) and Karwa (2012) for 500ºC, 800ºC, 1000ºC and 900ºC respectively. The ability to raise steel to this high temperature increases cost of production, since we can manage the cooling rate-controlled cooling and get better steel grade properties, it is imperative that lowering the initial surface temperature of steel be considered.

There is a prospect in exploring more fluids for jet impingement cooling of steel, this will give new steel property for designer's desired applications. Also the simultaneous or separate cooling of the sampled steel at top and bottom surfaces or inclined and opposite angles for a needed heat transfer energy balance that will give a better rate of cooling and good steel grades.

METHODOLOGY

Experiments were conducted for both air, water and other jets impinging fluids, top and bottom surface cooling, conventional and inclined cooling processes on steel plate surfaces. The same impingement configuration was employed for all the processes and fluids as it is obtainable in the steel industry. However different fluid flow test loops supplied the jets for different fluids. A schematic of the test loops used for each working fluid is shown in figure 1. Air is supplied from the building compressed air supply. The flow rate through the test system was controlled using a pressure monitored lever valve. Precision Gas Flow Meter recorded both the air flow rate in standard liters per minute (SLPM) and temperature on entry to the jet impingement test system. The water test loop is a closed system. A large tank filled with water acts as a reservoir. Water from the reservoir is circulated through the flow loop using a centrifugal pump or positive displacement pump of different capacities depending on the researcher. The flow rate is controlled using an in-series gate valve combined with a parallel bypass valve. The flow rate is recorded from a glass tube flow meter, which itself can act as a valve, allowing finer flow rate control. The fluid then flows through the jet impingement test section and is returned to the water reservoir. The reservoir water temperature remains constant.

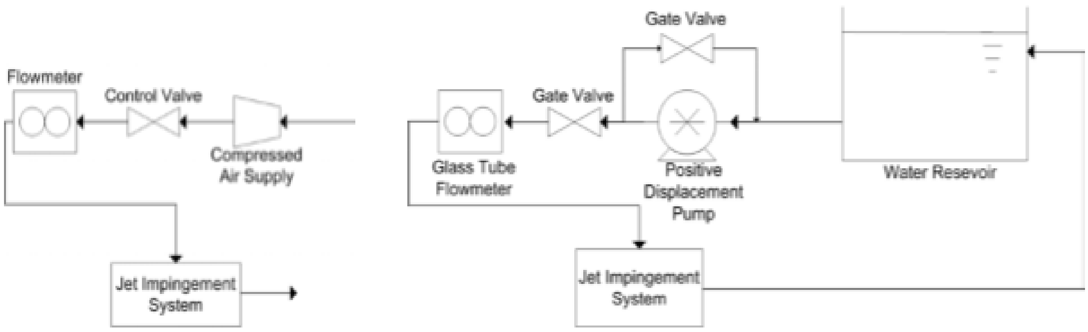

Figure 1: Schematic of Test Loop Air (left) and Water (right) as Working Fluids Gylnn et al, (2014).

In steel industries, rolling mills and designed for top surface cooling process and bottom surface cooling lacking. In the study of steel production in the laboratories, pilot scale run out table is designed to take care of the large space the rolling mills take, hence the study of the steel production in research laboratories.

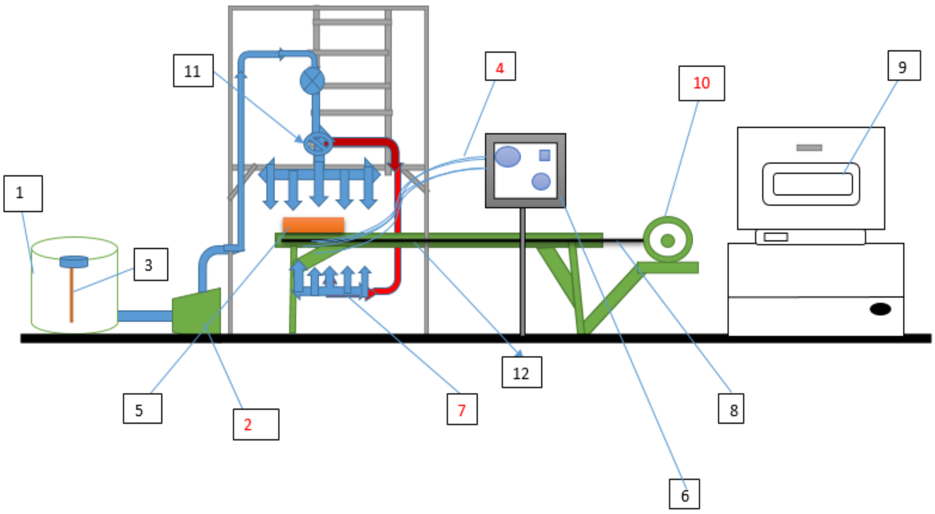

Figure 2: Schematic of Run-Out Table Combined Headers for Jet Impingement Cooling.

The temperature of the fluid (T_w), the surface temperature of steel sample (T_s), sub-cooled temperature of steel sample (T_{sub}), flow rate of fluid (Q), velocity of jet (V_j), pipe diameter (D), speed of the plate for conventional process (S_o) and impingement gap (H) are all the parametric variables that are obtained from experiment from any impingement fluid and from either of the processes. These parameters are either kept constant or varied for analysis, since most of them affect the rate of cooling which subsequently, affects steel grades.

Obtained experimental data is analyzed using empirical models, Onah et al (2018), used mechanistic model in their analyses for the prediction of zero surface temperature under pool boiling mechanism. Zhengdong, (2001) analyzed with numerical solution to solve finite element analysis of problem, where he implored Navier-stokes equation. Karwa, (2012), Ahmed, (2016) and Maharshi, (2017) used computer based numerical solution ANSYS FLUENT in solving the finite element analysis of their work. Md Lokman et al, 2014 used Computational Fluid Dynamics (CFD). For both 2D axisymmetric and 3D simulations the RANS model under steady and transient conditions as well as k-Ɛ turbulence model. The method of analysis, has space for the combine analytical approach of top and bottom surface process. The finite element analysis and the Navier stokes equations gives rooms for both analysis to be done

RESULTS AND DISCUSSIONS

Analysis of most experimental method records have shown one or two results of either top surface result or the bottom surface results. High initial surface temperature is part of the high cost of steel in the market since raising a steel to a degree centigrade has cost implication in the production of steel grades.

All water jet impingement cooling process has Leidenfrost phenomenon affecting the rate of cooling-At high temperature which is film boiling water evaporates quickly and a stable vapour layer is created between the hot plate and the water, which the layer obstructs the water from getting in contact with the hot plate and heat is transferred from the hot plate to liquid through conduction and radiation Gilles et al, (2019), Allowing this affect steel production continually, limits the heterogeneous nature if steel, but adopting new liquids, especially from agricultural raw materials, of those that can give paraffin oil and blending will be a replacement or near substitute to water.

There has been an error analyzing jet impingement cooling heat transfer one sided. To correct this error, a complete analysis of the jet impingement cooling heat transfer on both sides are imperative. Using top and bottom surface cooling simultaneously or separately but with same parameters should be done in steel industries rolling mills and in laboratories run-out tables ROT. Design, developed and installed in steel rolling mills with top and bottom surface nozzle headers and laboratory ROT with top and bottom nozzle headers for combine cooling process should be adopted as shown in Fig. 2.

CONCLUSIONS

For complete heat transfer energy balance all the results associated with single surface cooling process should be termed incomplete and the second process completed for a complete balance of the energy in heat transfer process using the recommended run-out table combined header. Agricultural products like tiger nut extracted juices and palm kernel oil and others should be used as jet impingement liquids. From Onah et al, (2018) they used initial surface temperature of 500ºC and still get martensitic steel grade property, it is obvious that 500ºC down to 400ºC initial surface temperature will give better steel grade with known property and less the cost of steel production which will have trickling down effect on the market cost of steel.

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